Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

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LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube [1] and acoustic resonator tube [2, 3] methods, in the frequency range of approximately 300 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [4-11] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation. Initial impedance tube work [12] indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective was to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

A secondary objective has been to investigate other ocean-bottom materials of opportunity utilizing the techniques and measurement instrumentation developed for this work. To date these materials have been gas-bearing sediments and seagrasses. Finally, the author participated in SW06 last FY and therefore a tertiary objective this FY was to participate in the analysis of some of the SW06 data in collaboration with other ONR PIs.

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14. ABSTRACT

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APPROACH

The impedance tube technique and has been adopted as a standard technique [13-15] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [16] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [17] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is +/- 0.14 dB in magnitude and +/- 0.8° in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It operates in the frequency range in which dispersion is expected (about 300 Hz to 30 kHz) in typical sandy sediments. It has been used to make measurements, which are presented below, but we are continuing to refine the technique and instrumentation. Two impedance measurement techniques can be utilized with the apparatus, [18, 19] which do not require movement of the sensors, and minimize errors due to sensor position uncertainty. The apparatus is also being used with the resonator method [2, 3] of measuring material properties. Finally, we have incorporated new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling is based on and extended from existing work for lossy fluid coupling in elastic waveguides, [19, 20] additional sample-wall boundary effects, [21] sample-fluid boundary effects [22] and asymmetric excitation. [23] The instrument will be used in the laboratory to investigate artificial and natural sediments *in vitro*.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant Research Professor at the University's Applied Research Laboratories (ARL:UT). In addition to oversight, Wilson contributes significantly to many tasks, including modeling, instrument and experiment design, construction and operation. Ryan L. Renfrow, a UTME senior and an Undergraduate Research Assistant on the project, serves as an electromechanical technician and provided machine shop, procurement and software support. Theodore F. Argo IV is a UTME Ph.D. student who contributes to all aspects of the project.

WORK COMPLETED

Primary Objective—Laboratory Sediment Investigation: Much time was devoted to developing a new impedance measurement technique, [19] referred to as the Mert method (after the method's originator) and outlined in Fig. 2. Excitation is provided at the bottom of the tube, and force and acceleration is measured between the piston and the prime mover. While this technique seemed like a great idea (removing the sensors from the medium), and worked successfully with a shorter tube down to 2 kHz, we experienced difficulty extrapolating the measurement technique to a larger tube and a lower frequency. For reference, measurements on water-saturated sand sediments made last year with a shorter tube (minimum frequency = 2 kHz) are shown in Fig. 3. Results obtained with distilled water using the new, longer tube and an appropriately scaled-up source, with a minimum frequency range of a few hundred Hz are shown in Fig. 4. Results in the new tube with water-saturated sand are shown in

Fig. 5. Several things are of note in these figures. The low frequency tube is exhibiting the expected behavior only at the nulls in impedance magnitude for the water-filled case. This would be enough information to extract sound speed at each null frequency, but the low-frequency tube is not working well at all with water-saturated sand. This is due to poor coupling and high losses at the piston interface. This problem is currently being resolved through the use of a water-filled interface layer. While we have not abandoned the Mert method, we did obtain measurements with water-saturated sand using the resonator method (Fig. 2) in the new low frequency tube. A comparison will be drawn in Figs. 6–8 between these latest measurements and a previous set of measurements.

Secondary Objectives—Gas-bearing Sediments: An opportunity became available in the previous FY (at no cost to this grant) to collaborate with the Seafloor Sciences Group at NRL-SSC on an experiment with gas-bearing sediments. An unprecedented set of contemporaneous acoustic measurements and computed x-ray tomography imaging scans were obtained on a variety of reconstituted natural sediments. These experiments were conducted at NRL-SSC in January 2006. Our 1-D acoustic resonator technique [3] was used to measure the sound speed inside the sediment samples. A high frequency (400 kHz) time-of-flight technique (using the Kevin Briggs ear-muffs apparatus [24]) was also used to measure the sound speed. The imaging scans yielded the bubble size distribution and the total void fraction (gas content) of the sediment. We found that Wood's equation was all that was necessary to describe the sound speed in a gas-bearing fluid-like sediment composed of kaolinite, distilled water and gas bubbles. Further analysis of the data collected at NRL-SSC last FY resulted in an invited paper and presentation in this FY. [26]

This collaboration also yielded permeability measurements on a sand sample that that had been the subject of a previous study. [25] The new permeability measurement was a significant addition to the results and yielded a new interpretation of the data and a new publication. [2]

Secondary Objectives—Seagrass Acoustics: Opportunity became available in the previous and present FY (at no cost to this grant) to collaborate with a seagrass biologist, Dr. Kenneth Dunton, of the University of Texas Marine Science Institute on an experiment with sediments containing seagrasses. The resonator technique was used to measure the effective low frequency acoustic properties of three gulf-coast species, *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). The work led to an invited paper and presentation in this FY [27] and a manuscript has been submitted. [28]

Tertiary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by this author and ARL:UT colleagues in SW06. Subsequent data analysis this year has shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions. CSS signals have been used for geoacoustic inversion [29] and for estimation of the frequency dependency of a sandy sediment sound speed. [30]

RESULTS

Primary Objective— Laboratory Sediment Investigation: A pair of sound speed measurements made with two different samples of water saturated sand are presented. In both cases, the material is reconstituted water-saturated sand in distilled water. Two different sands were used, as shown in Fig. 6, with different grain size distributions, as shown in Fig. 7. The sound speeds extracted from the well-sorted sand appear in the upper frame of Fig. 8 along with the Williams EDFM prediction. [11] We are now capable of performing most of the necessary measurements of the sand physical properties, including wet and dry density measurements (which lead to porosity), and permeability via ASTM D-2434. [31]. The measurements in the upper frame have now been published, [2] having been only submitted for publication this time last year. The sound speeds extracted from poorly-sorted sand appear in the lower part of Fig. 8. Note that there is a much greater spread in the measured mid-frequency sound speeds for the poorly-sorted case, but in both cases, there is ample evidence of dispersion. The EDFM does a good job of describing the well-sorted case, but a poorer job of describing the poorly-sorted case.

Secondary Objectives—Gas-bearing Sediments: The collaborative work with NRL-SSC resulted in the measurement of sound speed of a reconstituted gas-bearing kaolinite sediment and a natural mud from Bay St. Louis, MS. Contemporaneous measurements of the bubble size distribution were also obtained. A single image from the tomography scan is shown in Fig. 9. From this data, the overall sample void fraction was found. The acoustic experiment and the resulting sound speed measurement are shown in Fig. 10. This kaolinite sample was very fluid-like, yet it could still suspend bubbles. It was found that the sound speed observed in the acoustic experiment was perfectly consistent with the sound speed predicted by Wood's Equation, which is a mixture rule for bubbly liquids, in which the sound speed depends only on the gas-free sediment bulk density and the void fraction. To the PI's knowledge, this is the first quantitative verification of Wood's Equation for a gas-bearing sediment. Note that these results indicate that the only bulk sediment property required for the prediction of sound speed in shallow, fluid-like gas bearing sediments is the bulk sediment density and the total gas volume fraction. None of the other typical Biot sediment parameters are needed, nor is the bubble size distribution needed. Also note that the traditional high frequency time-of-flight measurement technique failed in the gassy kaolinite due to excessive attenuation.

The results for the Bay St. Louis (BSL) mud sample are shown in Fig. 11, but here, the simplified Wood's equation does not accurately describe the observed sound speed. A potential explanation is that, the bubbles were not evenly distributed (as they were in the kaolinite) and because of this inhomogeneity, the effective sound speed was perhaps also nonuniform, causing failure of the data analysis applied here. Another potential explanation is that the BSL mud exhibited higher shear rigidity than the kaolinite, causing the fluid model to fail. Note that there is a significant difference between the low frequency (200–800 Hz) measured sound speed (287 m/s) and the high frequency sound speed (1520 m/s @ 400 kHz), verifying expectation qualitatively.

Secondary Objectives—Seagrass Acoustics: Experiments were conducted using the resonator technique to asses the hypothesis that seagrass is acoustically dominated by its gas content, and that Wood's equation could be used to model sound propagation in seagrass beds as an effective medium. A typical result for the species *Thalassia testudinum* (turtle grass) is shown in Fig. 12. The two curves show plant volume fraction $V_{\mathrm{leaves}}/V_{\mathrm{tot}}$ (measured by acoustic and image-based techniques) as a function of the number of leaves placed inside the resonator. The black curve yields an acoustically-determined plant internal void fraction $\chi_{\mathrm{leaf,\,a}} = 0.034$, via best fit of the equation at the top of the figure. The actual plant internal void fraction, determined using microscopic cross-section image analysis (Fig. 13), was found to be $\chi_{\mathrm{leaf}} = 0.23$. Similar results were found the *Thalassia testudinum* (turtle grass) rhizomes (underground root structures) and the leaves and rhizomes of the other two species tested, *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). This refutes the above hypothesis and indicates that forward models of sound propagation and scattering in seagrass beds will require not only knowledge of the gas content, but knowledge of the plant tissue properties and structures, too. Therefore, understanding the acoustics of seagrass will be a significantly more difficult problem than previously thought. Additional details of this work are presented in [27] and the work has been submitted for publication. [28]

Tertiary Objective—Sediment Attenuation in SW06: The frequency dependency of a sandy sediment sound speed along a track in SW06 was analyzed [30] and found to exhibit low frequency attenuation in good agreement with predictions of the EDFM. [11] The results are shown in Fig. 14, and the new low frequency attenuation values show a slope proportional to the frequency squared, in contrast to higher frequency attenuation values which show a slope proportional to the square root of frequency.

IMPACT/APPLICATIONS

The Biot-based description of sound propagation within sandy marine sediments is gaining support in the ocean acoustics and related research communities, but we are also coming to the conclusion that it not fully adequate. The new laboratory results reported here indicate that the EDFM [11] correctly predicts the mid (0.8–5 kHz) and high frequency (20–300 kHz) sound speed in water saturated sand, but there is more variability in the measured data than can be explained by the EDFM for poorly-sorted sands. Low frequency (80–2000 Hz) attenuation data from SW06 are also well described by EDFM and clearly follow the low frequency limiting slope of frequency squared. We are continuing our efforts to get ever-lower- frequency and more accurate laboratory measurements with and increased understanding of the measurement uncertainties.

Fluid-like shallow gas-bearing sediments were shown to have acoustic properties that depend only on the sediment bulk density and the void fraction as given by a simplified version of Wood’s Equation. Two types of tissue from three different species of seagrass where shown to depend on tissue acoustic properties in addition to the gas content, and hence were not described by Wood’s equation.

As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems. A better description of bottom interaction will increase our ability to detected, localize and classify targets in littoral environments. The same can be said for buried objects. The CSS performed very well during SW06 is proving to be a useful tool for ocean acoustics experiments.

TRANSITIONS

This PI is slated to receive $500k over two years (starting in 2008) from the Naval Oceanographic Office for further development of the combustive sound source (CSS) as a replacement for explosives in ocean surveys.

This PI received $15.7k from the Naval Surface Warfare Center-Panama City to perform laboratory measurements of sound speed on gas-bearing sediments collected during a mine hunting exercise, using the resonator method developed with the present grant.

This PI received $110k from the Naval Research Laboratory to study the acoustic properties of methane hydrates using the resonator method developed with the present grant.

RELATED PROJECTS

SAX99: Sediment Acoustics Experiment 1999
From the project web page: SAX99 addresses high-frequency sound penetration into, propagation within, and scattering from the shallow-water seafloor at a basic research (6.1) level.
http://www.apl.washington.edu/programs/SAX99/Program/prog.html

SAX04: Sediment Acoustics Experiment 2004
From the project web page: The overall objective of SAX04 is to better understand the acoustic detection at low grazing angles of objects, such as mines, buried in sandy marine sediments. One component of the SAX04 work is designed to collect data and gain a greater understanding of high-frequency sound penetration into, propagation within, and scattering from the shallow water seafloor at a basic research level. A second component is designed to provide data directly on acoustic detections of buried mine-like objects at low grazing angles.
http://www.apl.washington.edu/projects/SAX04/summary.html

Other ARL:UT sediment researchers: Marcia Isakson and Nicholas Chotiros both conduct research on sound propagation in marine sediments.

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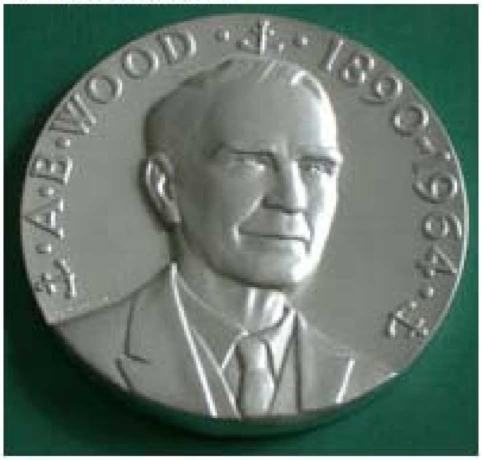
HONORS/AWARDS/PRIZES

This grant's PI, Preston S. Wilson of The University of Texas at Austin received the A.B. Wood medal from the Institute of Acoustics in the United Kingdom.

A B WOOD MEDAL



The A B Wood medal and attendant prize is awarded in alternate years to acousticians domiciled in the UK or Europe and in the USA or Canada. It is aimed at younger researchers, preferably under the age of 35 in the year of the Award, whose work is associated with the sea. Following his graduation from Manchester University in 1912, Albert Beaumont Wood became one of the first two research scientists at the Admiralty to work on antisubmarine defence. He designed the first directional hydrophone and was well known for the many contributions he made to the science of underwater acoustics and for the help he gave to younger colleagues. The medal was instituted after his death by his many friends on both sides of the Atlantic and was administered by the Institute of Physics

FIGURES

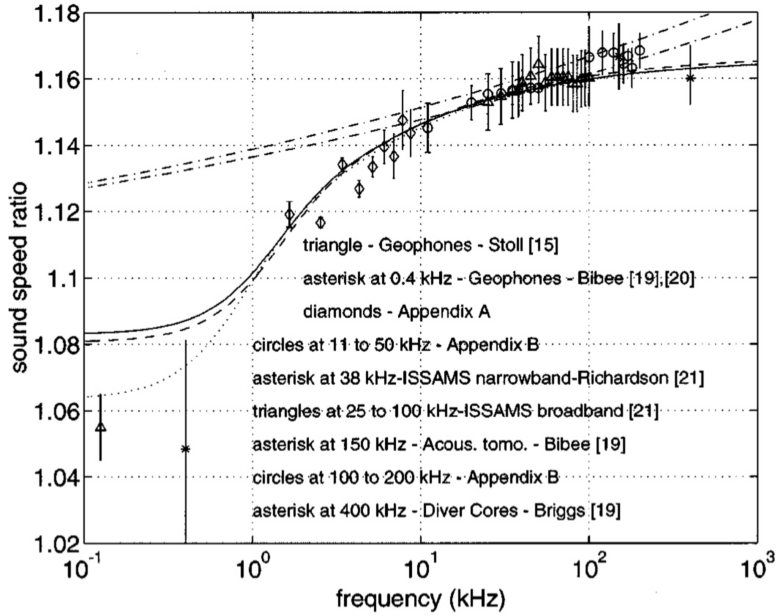


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [32]. The theoretical curves are: solid line=Biot/Stoll[10]; dashed line=Williams[11], dash-dot lines=Buckingham's model for two values of fluid viscosity[9]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [32].)

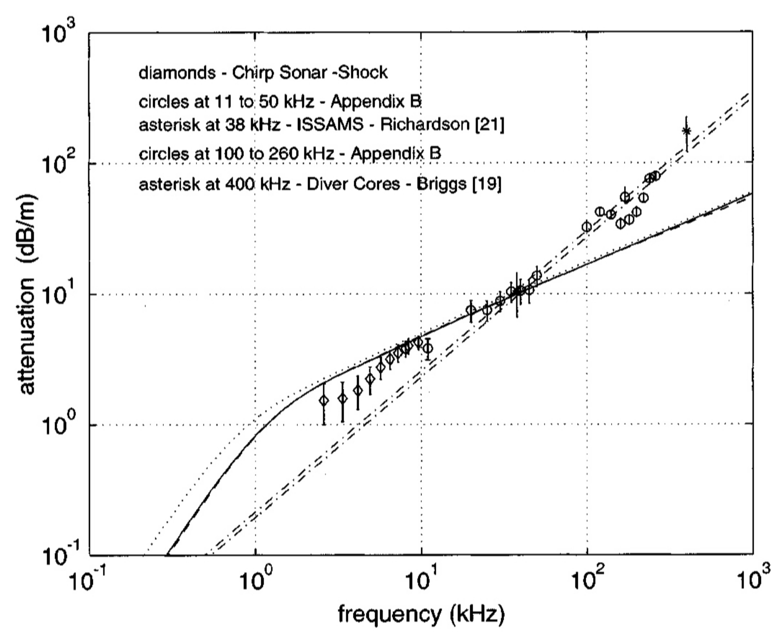


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [32].) Also note that there is attenuation data below about 3 kHz.

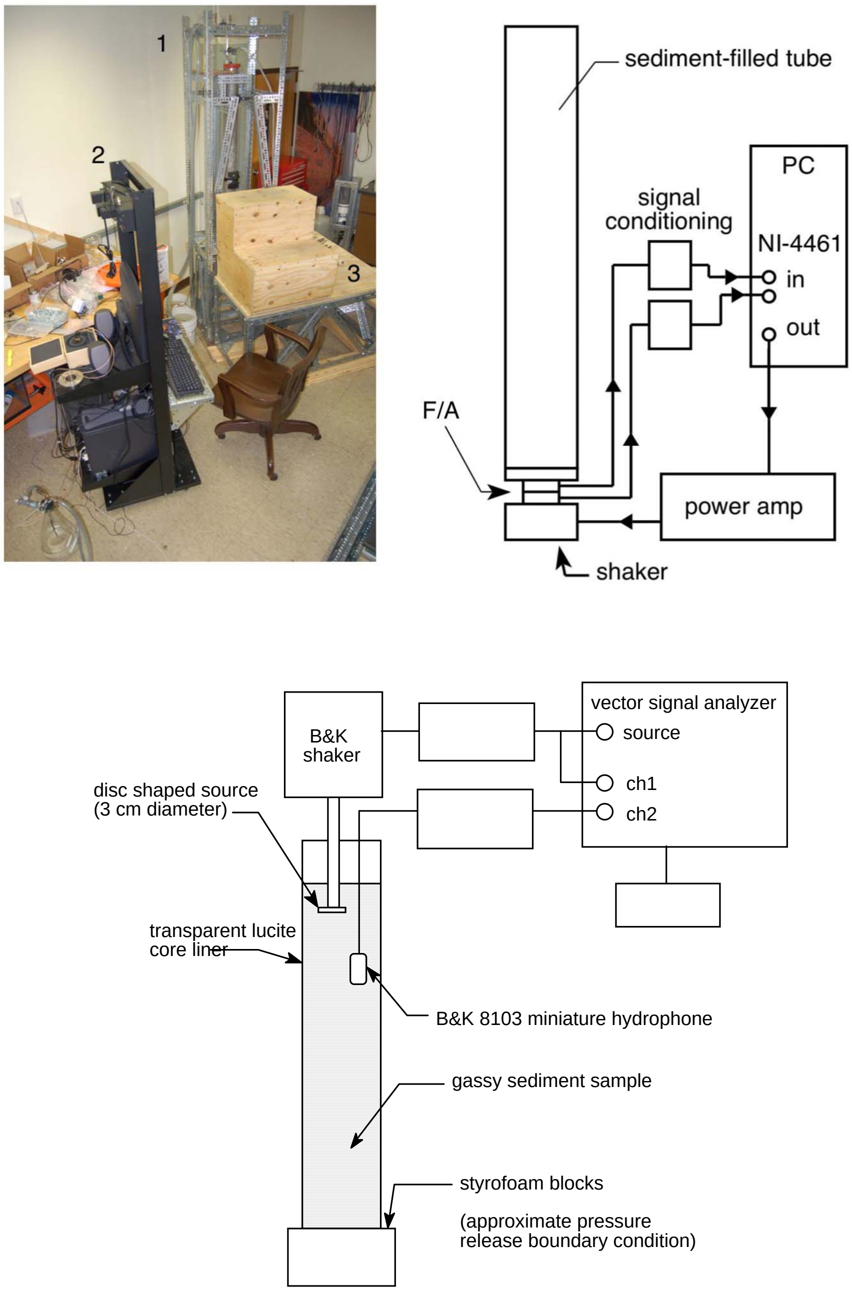


Fig. 2. The upper left is a photograph of the impedance tube facility: the support frame and tube (1), the computer and data acquisition system (2), and the scaffolding (3). On the upper right, the schematic of the Mert apparatus [19] is shown. In the lower frame, a schematic of the resonator method is shown.

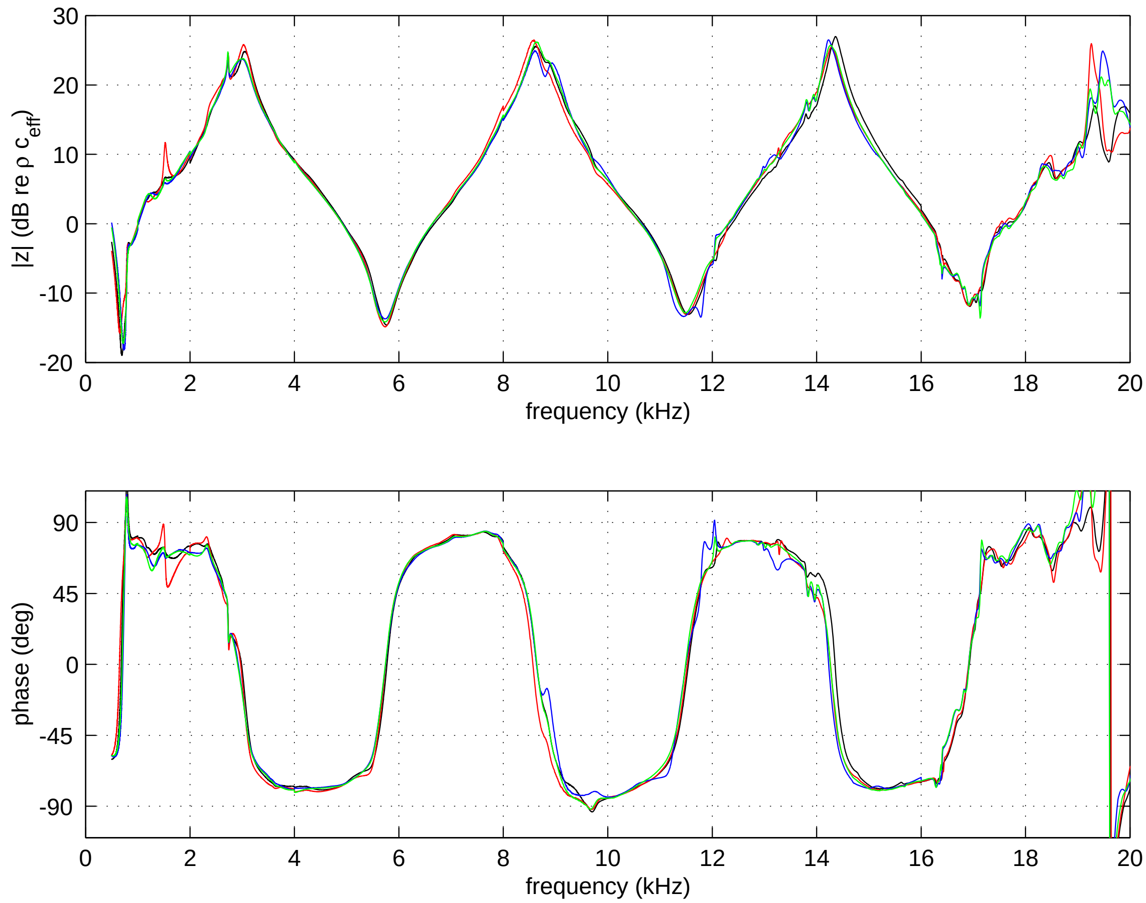


Fig. 3. A short (min frequency = 2 kHz) impedance tube was used last year to obtain the data shown here, which is included for comparison to new data in Figs. 5–6. Measured impedance of unwashed/unsieved and washed/sieved reconstituted sand sediment samples plotted together for comparison. The red and black curves are for the unwashed case and the blue and green curves are for the washed case. Little significant difference is seen.

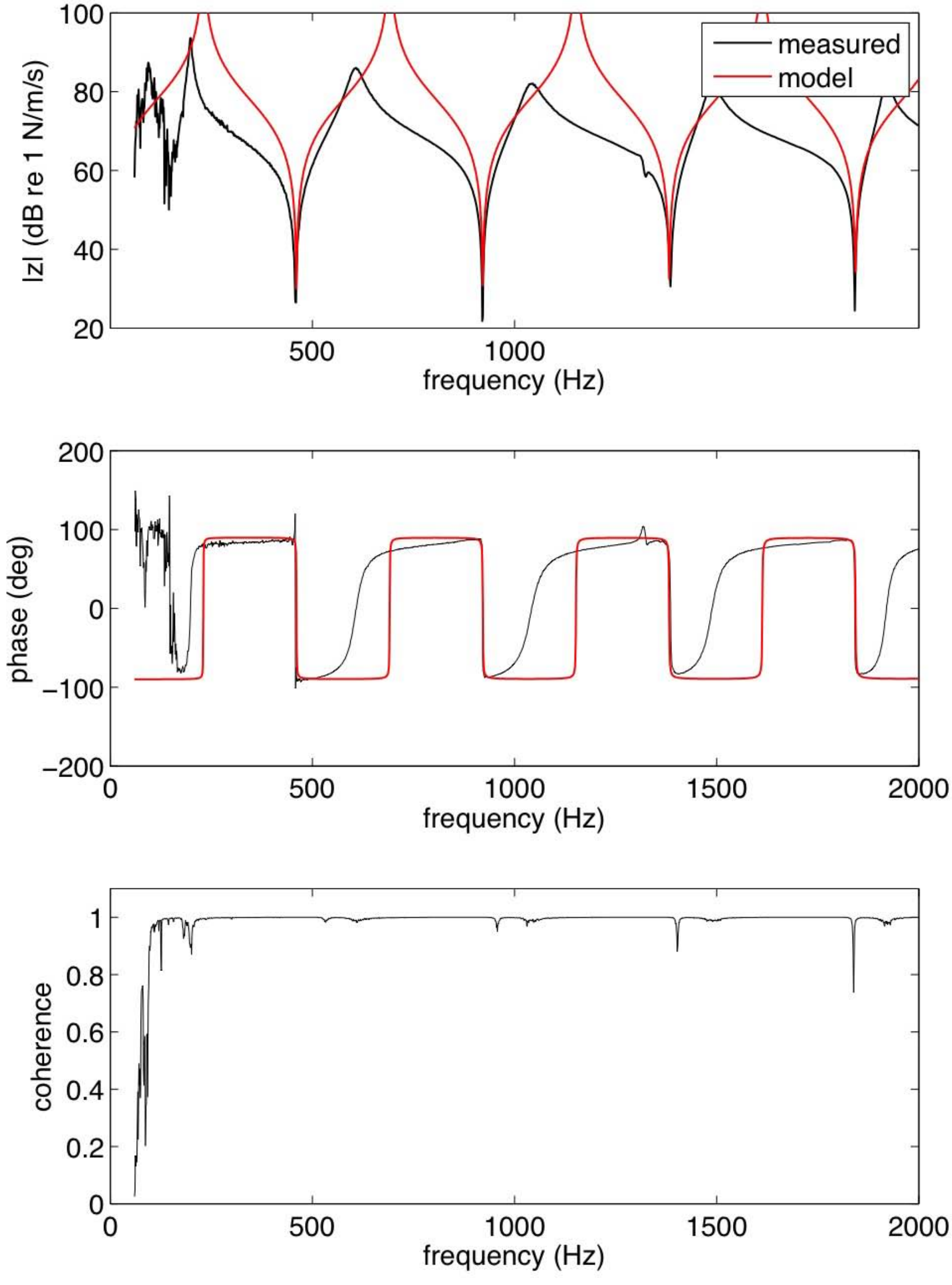


Fig. 4. The long (min frequency = 200 Hz) impedance tube developed this year was used to obtain the data shown here. The material that filled the tube was distilled water. Note that the measured and predicted impedance magnitude and phase do not agree, except for at the minima in magnitude and the corresponding frequencies in phase.

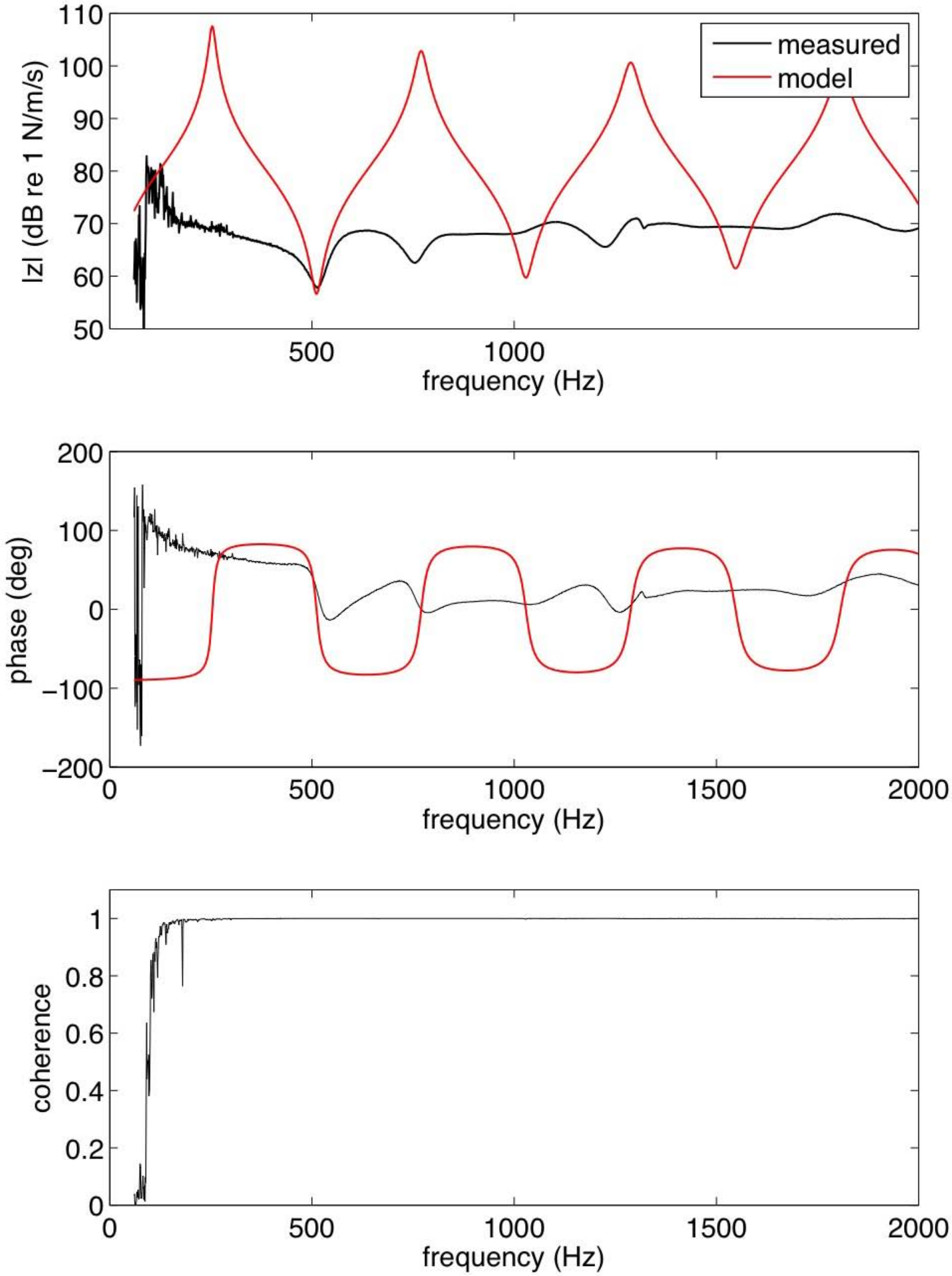


Fig. 5. The long (min frequency = 200 Hz) impedance tube developed this year was used to obtain the data shown here. The material that filled the tube was reconstituted water-saturated sand. Note that the measured and predicted impedance magnitude and phase agree even less than in Fig. 4.

Fig. 6. The photo shows two samples of sand. On the left, the sample is poorly sorted. The presence of larger grains adds a long tail to the grain size distribution function. On the right, the sample is well-sorted.

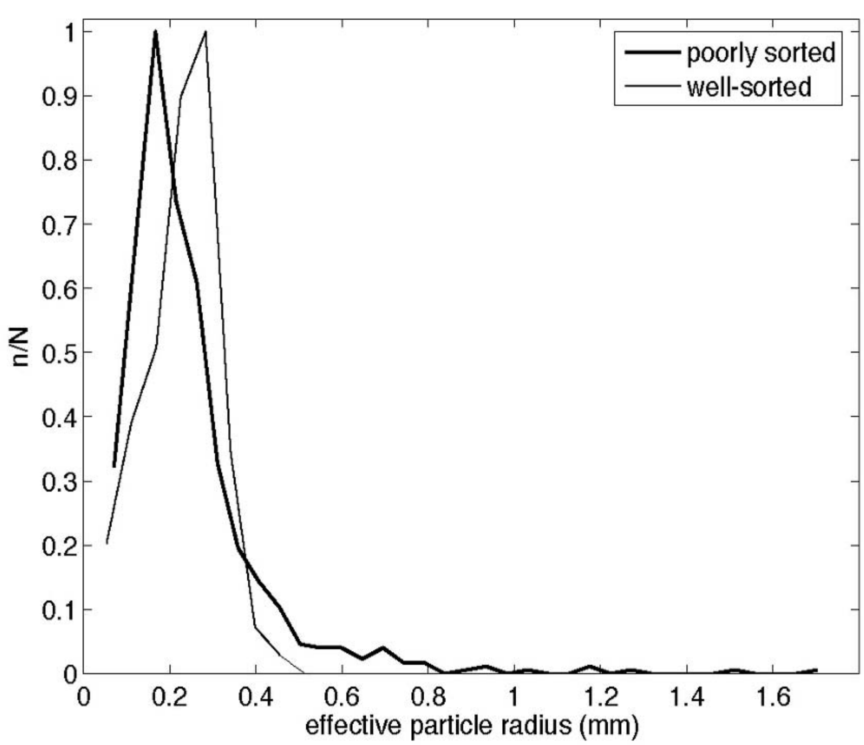


Fig. 7. Measured grain size distribution functions for the two samples of sand shown above.

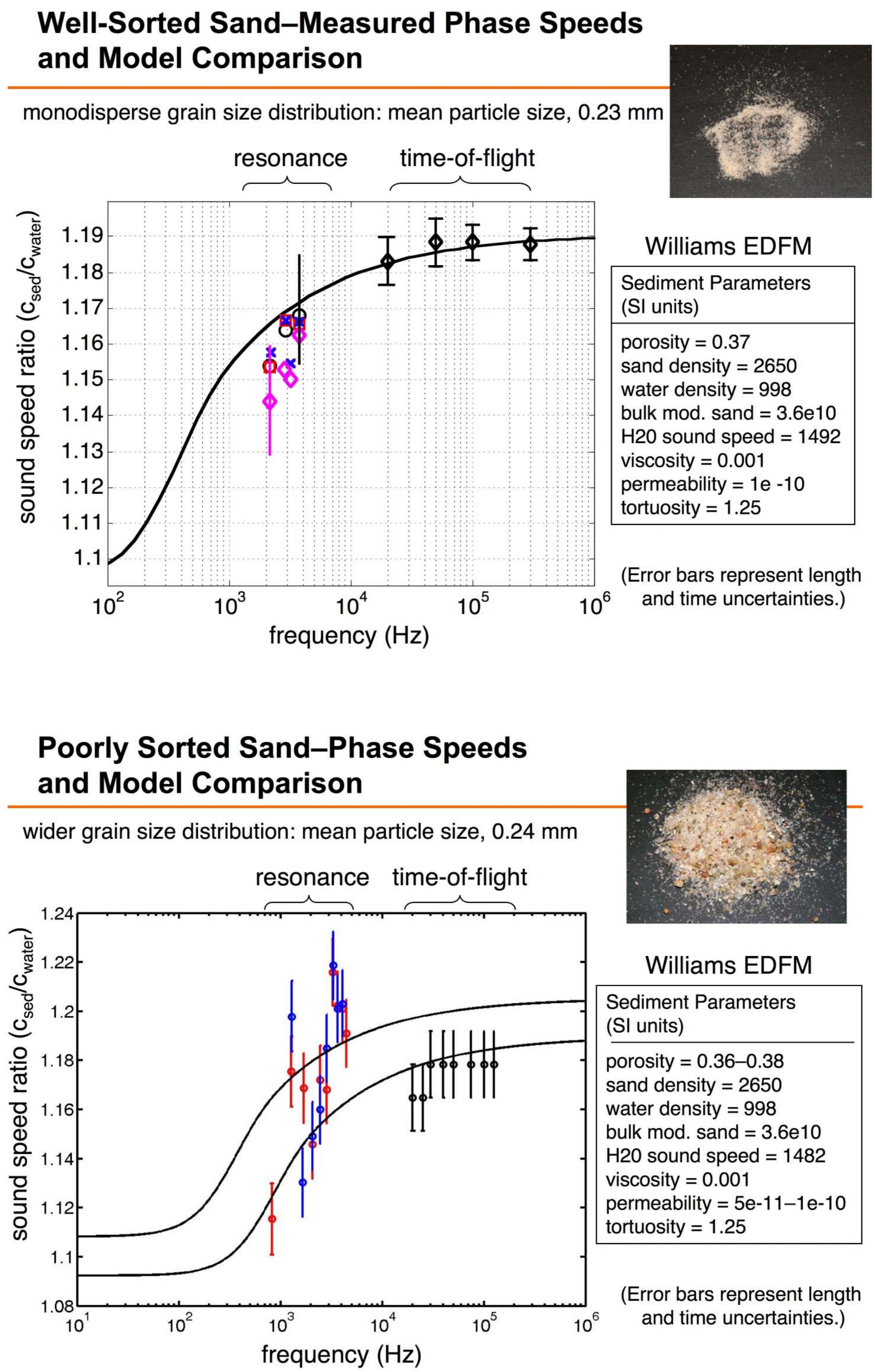


Fig. 8. The measured sound speed for well-sorted and poorly sorted sand sediments are shown above in the upper and lower frames, respectively. There is greater variation in the measurements for the poorly sorted sand. In both cases, the different colors represent measurements in different sub-regions of each sample. The upper figure was adapted from [2].

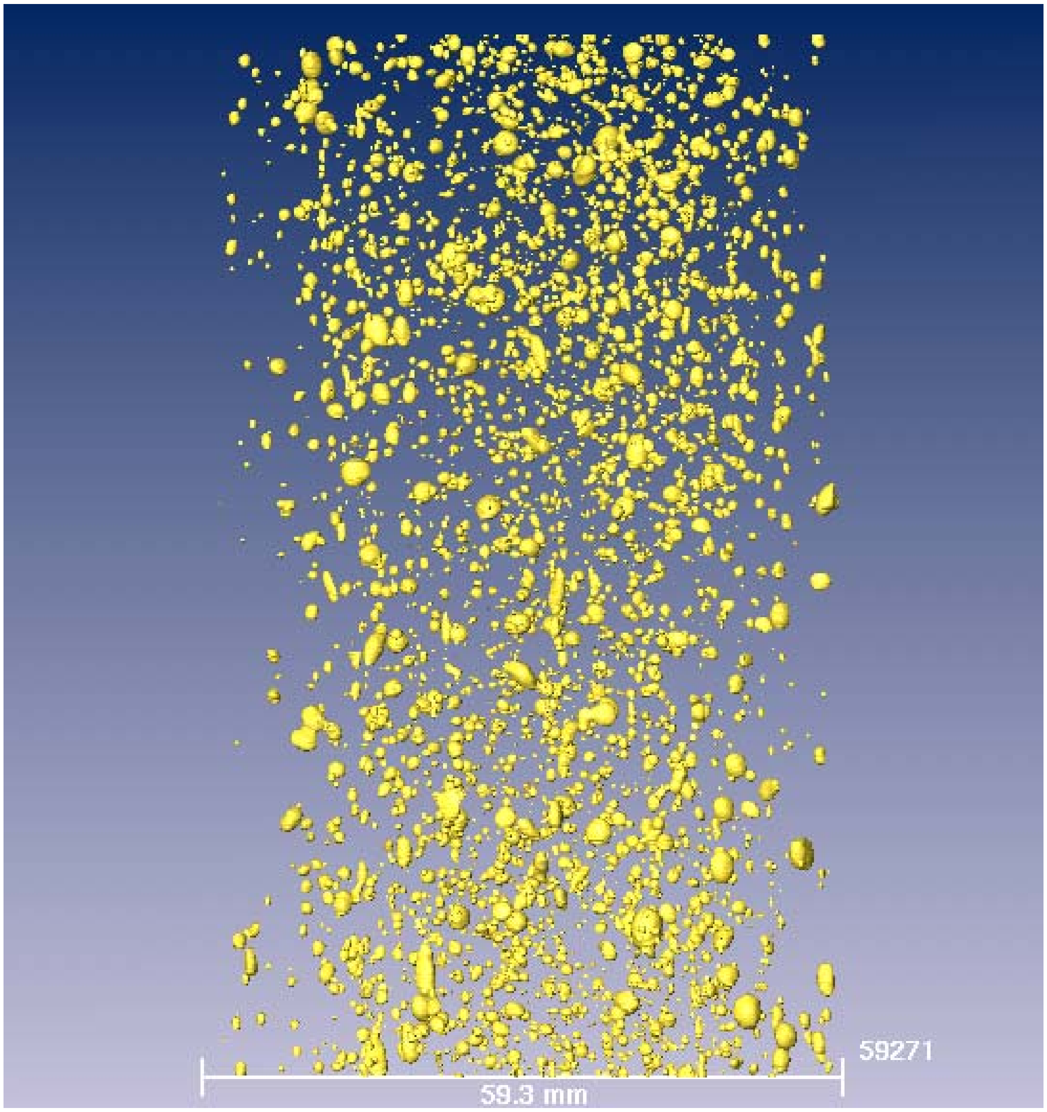


Fig. 9. A single image from the computed x-ray tomography scan of the kaolinite sediment sample contained within the 1-D acoustic resonator. The yellow blobs are air bubbles. The data was manipulated to give the volume of each bubble, and the total void fraction and the effective spherical bubble size distribution were determined.

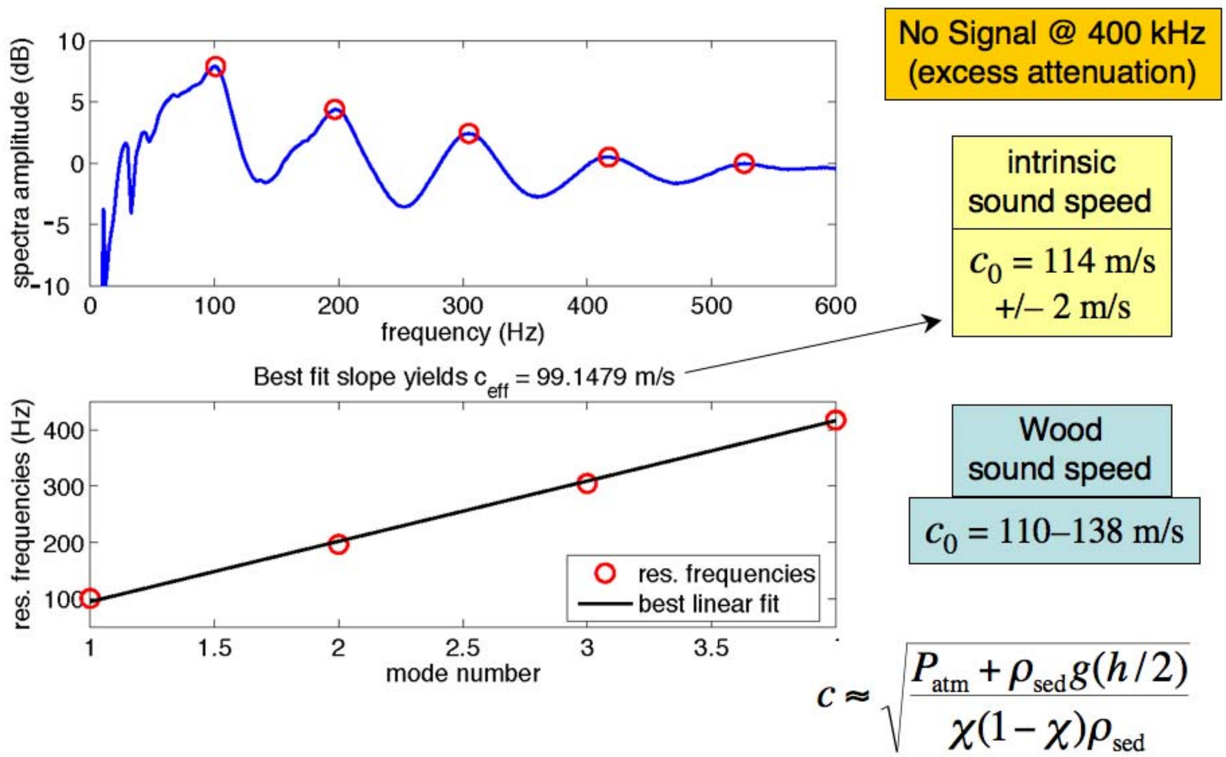


Fig. 10. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with reconstituted bubbly kaolinite sediment. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. A simplified version of Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from the image analysis, as discussed in Fig. 9. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm}, the acceleration due to gravity g, and the sediment column height h. The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters. The simplified Wood's equation accurately describes the measured sound speed. In the orange box on the upper right, the high frequency time-of-flight measurement is shown, which in this case yielded no result.

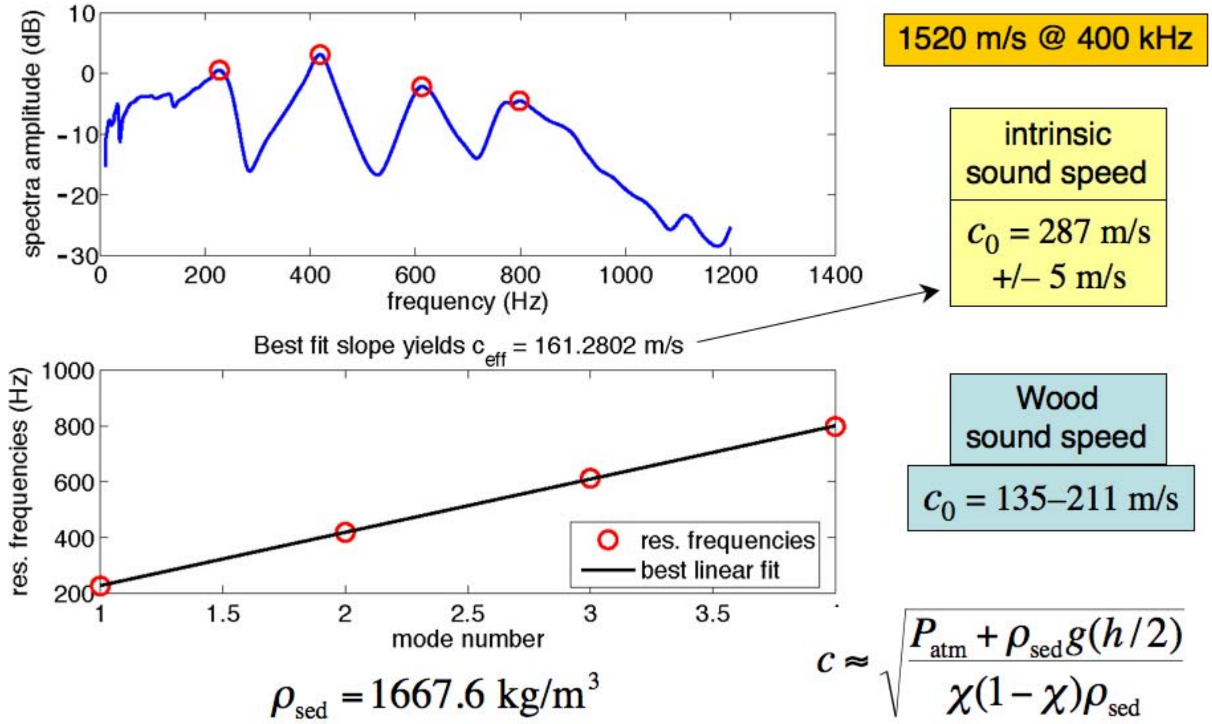


Fig. 11. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with a natural mud sediment collected from Bay St. Louis near NRL-SSC. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. A simplified version of Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from image analysis, similar to that shown in Fig. 9. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm}, the acceleration due to gravity g, and the sediment column height h. The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters. The simplified Wood's equation does NOT accurately describe the measured sound speed. In the orange box on the upper right, the high frequency time-of-flight measurement is shown.

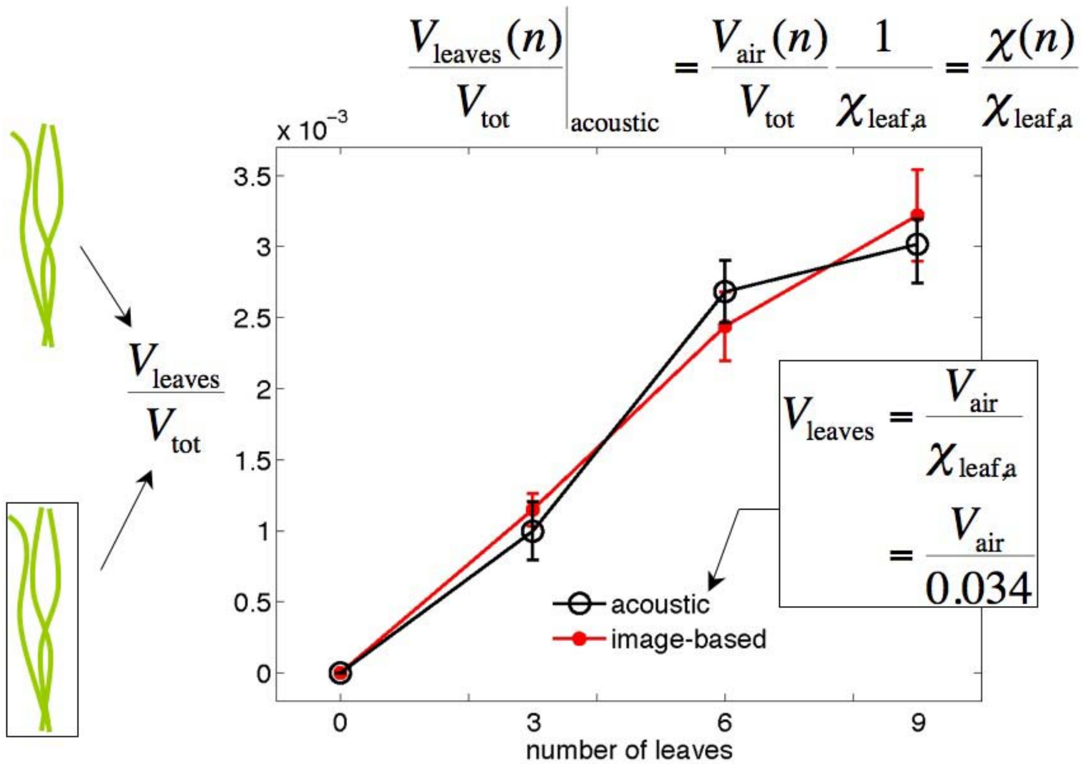


Fig. 12. The apparent acoustic volume fraction of thalassia leaves is compared to the volume fraction obtained by image analysis of the leaf physical volume. The black curve yields an internal leaf void fraction of 0.034.

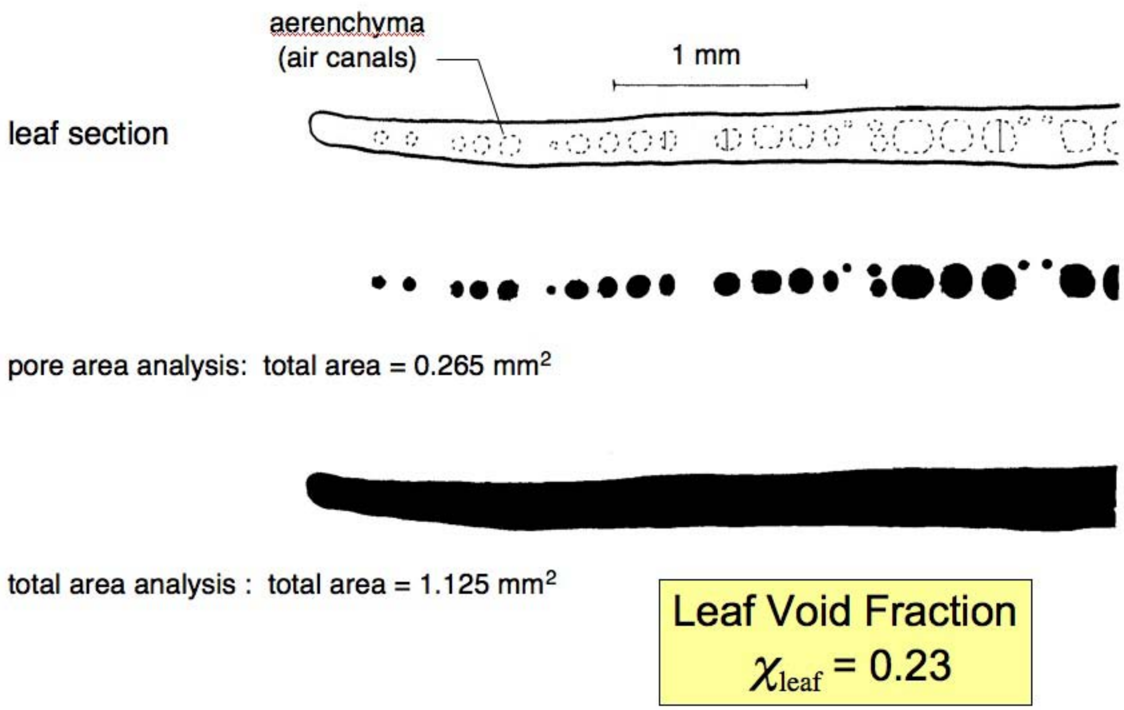


Fig. 13. The actual internal leaf void fraction was determined to be 0.23 from this microscopic cross-section image analysis.

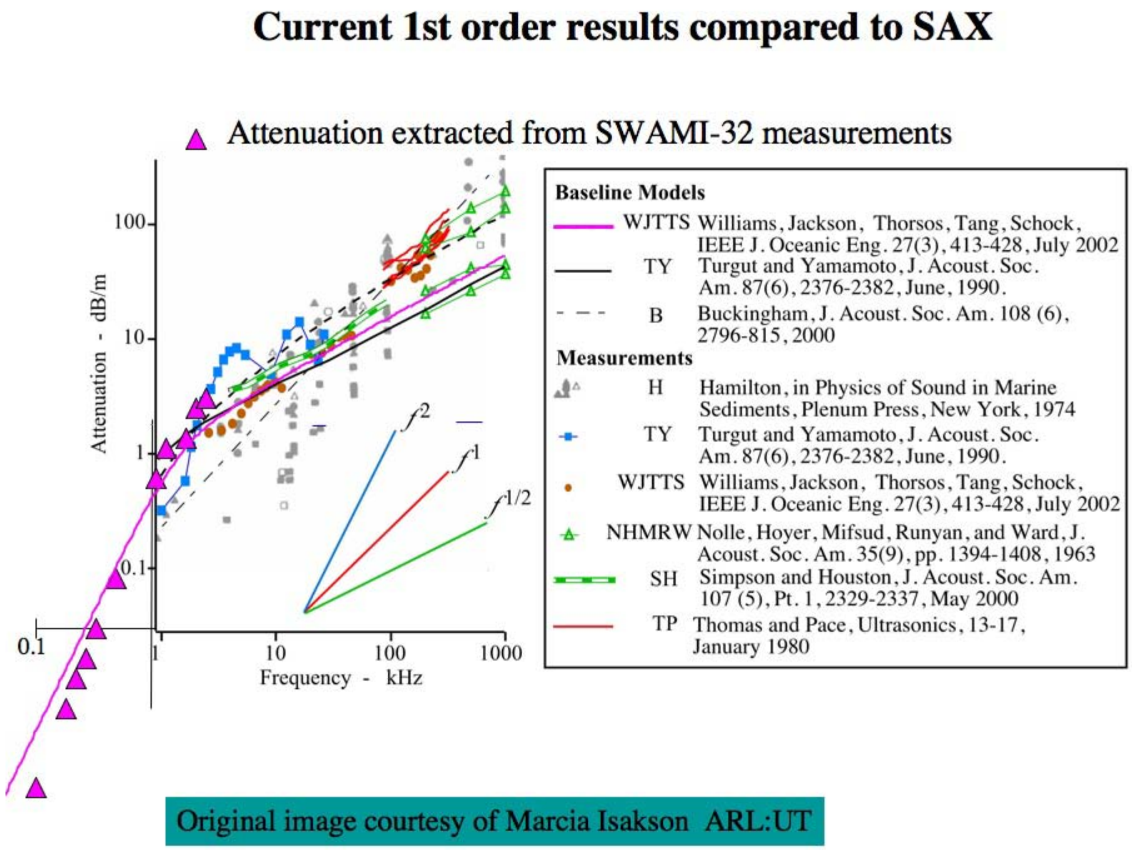


Fig. 14. The large purple triangles represent sandy sediment attenuation values inferred by matching measured long range transmission loss curves from SW06 with model predictions in which the sediment attenuation is the only fit parameter. The purple curve is the prediction of the EDFM with input parameters from SAX99. Note that these extrapolated attenuation values go below 100 Hz and clearly show a different slope than the higher frequency measurements.